Magnetic Ordering in the Superconducting Weak Ferromagnets $RuSr_2GdCu_2O_8$ and $RuSr_2EuCu_2O_8$

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Rationale for studying $RuSr_2GdCu_2O_8$

1-layer Compounds

La_2CuO_4 is a SC with Tc=40K

Sr_2RuO_4 is a SC with T_c<1K

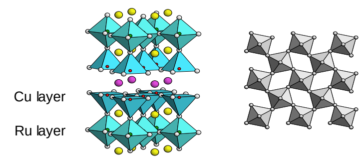
2-layer Compounds

$(La,Ca)_3Cu_2O_6$ is a SC with T_c=60K

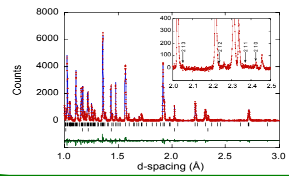
$Sr_3Ru_2O_7$ is a FM with T_M=104K

The Ru-1212 ruthenocuprates, e.g., $RuSr_2GdCu_2O_8$ have alternating Ru-O and Cu-O layers and exhibit the coexistence of bulk superconductivity and ferromagnetism.

Crystal structure of $RuSr_2GdCu_2O_8$

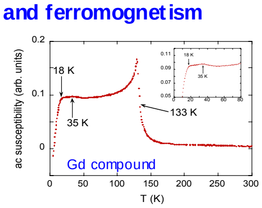


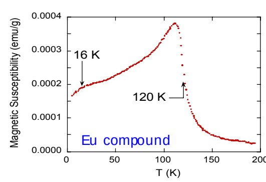
The crystal structure is like that of $YBa_2Cu_3O_7$ where the Cu-O "chain" layer is replaced by a layer of corner-linked RuO_6 octahedra. These octahedra rotate to accommodate the large Ru-O bond length. This requires a doubled unit cell.

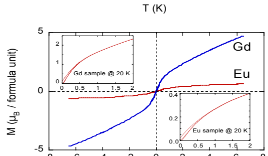


The crystal structure was determined by neutron powder diffraction. The superlattice reflections (indexed in the inset) define the larger unit cell and the nature and magnitude of the RuO_6 octahedral rotation.

Experimental evidence for coexisting superconductivity and ferromagnetism

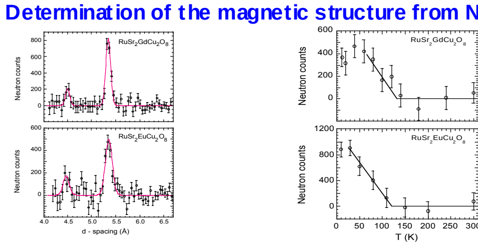


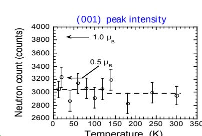




Susceptibility measurements show a magnetic transition at higher temperature followed by a diamagnetic transition at lower temperature. Hysteresis loops show that the magnetic ordering includes a ferromagnetic component. The hysteresis loops for the Gd compound are about 6 times larger (in area).

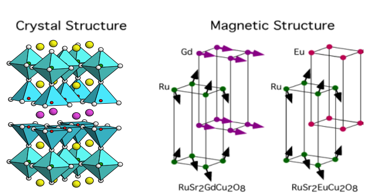
Determination of the magnetic structure from NPD





Neutron diffraction data show G-type antiferromagnetic ordering In both structures [(1 0 1/2) and (1 0 3/2) peaks] with temperature dependence consistent with the known magnetic transition temperatures. Ferromagnetic ordering perpendicular to the c axis would be manifest as additional intensity in the (0 0 1) peak. We see no evidence for this (in $RuSr_2GdCu_2O_8$) within the sensitivity of our measurement (~0.3 μ_B).

The magnetic structure



The dominant magnetic structure is G-type antinferromagnetic, with Ru moments antiparallel in all three crystallographic directions. However, such a magnetic structure cannot explain the hysteresis loops seen in magnetization measurements. The ferromagnetic moment must arise from a small canting of the Ru moments. For the Gd compound, where Gd has a large moment, this canting produces a net moment at the Gd site and the Gd moments also order, adding to the ferromagnetic moment. For the Eu compound, where Eu has no moment, no such effect occurs. This explains the 6-times larger hysteresis loops for the Gd compound compared to the Eu compound.

Conclusions

- Both $RuSr_2GdCu_2O_8$ and $RuSr_2EuCu_2O_8$ have G-type antiferromagnetic structures as the dominant magnetic ordering of Ru moments.
- Neutron diffraction sees no ferromagnetic ordering. It is presumed to be below the level of sensitivity of the technique (not surprisingly).
- The weak ferromagnetism probably comes from canting of Ru moments to produce a small net ordered moment in the plane.
- In the Gd compound, induced ordering of the large Gd moments (~7 μ_B) leads to the 6-times larger hysteresis loops.

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